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LHC Signatures of a Vector-Like Top Partner and Charged Higgs boson in the 2HDM-II

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Outline

SM Higgs Doublet and Degrees of Freedom

➠ The SM contains one complex scalar doublet with hypercharge $Y = \frac{1}{2}$:

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\eta) \end{pmatrix} .$$

➠ The Higgs potential:

$$V(\Phi) = -\mu^2 \Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2, \qquad \mu^2 > 0,\ \lambda > 0.$$

➠ EWSB: $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$ with

$$v \simeq 246\, GeV, \qquad v^2 = \frac{\mu^2}{\lambda}.$$

➠ A complex doublet has 4 real d.o.f. After EWSB:

- ★ 3 Goldstone bosons $\to W_L^\pm, Z_L$,
- ★ 1 physical scalar: the Higgs boson h.

EWSB and Mass Generation in the SM

- Gauge boson masses from the kinetic term:

$$\mathcal{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi),$$

  with

$$D_\mu \Phi = \left(\partial_\mu - i\frac{g}{2}\tau^i W_\mu^i - i\frac{g'}{2} B_\mu \right) \Phi.$$

- After EWSB:

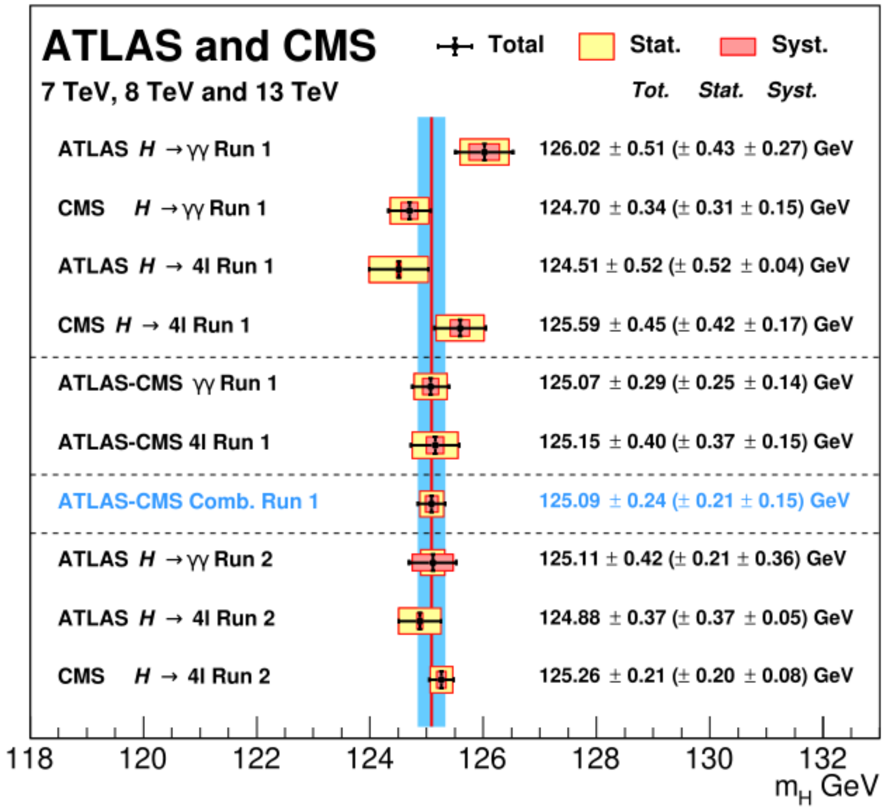
$$m_W = \frac{gv}{2}, \qquad m_Z = \frac{\sqrt{g^2 + g'^2}}{2} v, \qquad \rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \text{ (tree level)}.$$

- Fermion masses from Yukawa couplings:

$$\mathcal{L}_Y^{SM} = -y_f \bar{f}_L \Phi f_R + \text{h.c.} \quad \Rightarrow \quad m_f = \frac{y_f v}{\sqrt{2}}.$$

- This minimal structure is highly predictive but may be only an effective description of a richer scalar sector.

- Precision measurements from ATLAS and CMS confirm the Higgs mass near 125 GeV and couplings close to SM values.
- However, no additional scalars have been observed so far, so the **structure of the Higgs sector remains open**.
- The 2HDM is a minimal and well-motivated extension:
  - ★ richer spectrum: h, H, A, $H^{\pm}$,
  - ★ modified couplings and new production/decay channels.
- Such frameworks remain consistent with current Higgs data and provide targets for future precision and discovery programs.



ATLAS and CMS Higgs mass measurements (Run 1 and 2)

Why Go Beyond the SM Higgs Sector?

- The SM Higgs sector:
  - ★ explains EWSB and tree-level $\rho \approx 1$,
  - ★ but is not unique.
- Extended scalar sectors can address:
  - ★ additional CP-violation (electroweak baryogenesis),
  - ★ dark matter (inert doublet, singlet extensions),
- Precision Higgs couplings (LHC, HL-LHC, future colliders) are sensitive to deviations induced by extra Higgs fields.
- The simplest such extension: add a second scalar doublet $\Rightarrow$ Two-Higgs-Doublet Model (2HDM).

Two-Higgs-Doublet Model: Field Content

- Add a second Higgs doublet with $Y = \frac{1}{2}$:

$$\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ \\ \frac{1}{\sqrt{2}}(v_{1,2} + \rho_{1,2} + i\eta_{1,2}) \end{pmatrix}, \qquad v_1^2 + v_2^2 = v^2.$$

- Define the angle β through the vev ratio:

$$\tan\beta = \frac{v_2}{v_1}, \qquad v \simeq 246\text{ GeV}, \qquad v_1 = v\cos\beta,\ v_2 = v\sin\beta.$$

- After EWSB, the neutral CP-even states are related to (ρ_1, ρ_2) via the mixing angle α:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}.$$

- The CP-odd sector is rotated by β:

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix},$$

where G^0 is the neutral Goldstone boson and A the physical CP-odd Higgs.

- Similarly, the charged sector is rotated by β:

$$\begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix},$$

with $G^\pm$ the charged Goldstones eaten by $W^\pm$ and $H^\pm$ the physical charged Higgs bosons.

The most general renormalizable, gauge-invariant $SU(2)_L \times U(1)_Y$ scalar potential for two $Y = \frac{1}{2}$ doublets $\Phi_{1,2}$ is:

$$\begin{aligned} V(\Phi_1, \Phi_2) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\ & + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\ & + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\ & + \left\{ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} \right\}. \end{aligned} \tag{1}$$

- **Possible sources of CP violation:**
  - **Explicit CP violation** from complex parameters: m_{12}^2, $\lambda_{5,6,7}$ can all be complex.
  - **Spontaneous CP violation** from complex vevs:

    $$\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i e^{i\theta_i} \end{pmatrix}, \qquad \theta_1 - \theta_2 \neq 0.$$

    If all couplings are real but the vacuum develops a relative phase, CP is spontaneously broken.
- **Conditions for a CP-conserving scalar sector:**
  - there exists a basis where all couplings m_{ij}^2, λ_i are **real**,
  - and the vacuum is **real**: $\theta_1 - \theta_2 = 0$.

  This ensures no mixing between CP-even and CP-odd fields, giving a block-diagonal neutral mass matrix.
- **In the rest of the talk**: We focus on the CP-conserving 2HDM, since it is predictive, widely used in collider phenomenology, and consistent with current constraints.

The Z_2 Symmetry and the FCNC Problem

- In a general 2HDM, both doublets may couple to the same fermion type:

$$\mathcal{L}_Y \sim \bar{Q}_L (Y_1^d \Phi_1 + Y_2^d \Phi_2) d_R + \cdots$$

  This leads to **tree-level flavor-changing neutral currents (FCNCs)** through the neutral scalars.

- To avoid this, impose a **discrete Z_2 symmetry**:

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2,$$

  and assign each fermion species to couple to only one of the two doublets.

- The Z_2 symmetry has several roles:
  - eliminates tree-level FCNCs,
  - forbids the dangerous $\lambda_{6,7}$ terms, simplifying the potential,
  - naturally leads to (or is consistent with) CP-conserving scenarios,
  - allows a **soft breaking** term m_{12}^2, crucial for realistic mass spectra.

- Assigning fermions to $\Phi_{1,2}$ yields four consistent models:

Type	up-quarks	down-quarks	leptons
I	Φ_2	Φ_2	Φ_2
II	Φ_2	Φ_1	Φ_1
X (lepton-specific)	Φ_2	Φ_2	Φ_1
Y (flipped)	Φ_2	Φ_1	Φ_2

- In this work, we adopt the **Type-II 2HDM**, motivated by supersymmetry and widely used in collider phenomenology.

The Alignment Limit in the 2HDM

- In the CP-conserving 2HDM, the couplings of the CP-even states to gauge bosons are:

$$g_{hVV} = \sin(\beta - \alpha) g_{hVV}^{SM}, \qquad g_{HVV} = \cos(\beta - \alpha) g_{hVV}^{SM}.$$

- **Alignment limit:**

$$\cos(\beta - \alpha) \to 0 \quad \Rightarrow \quad h \text{ has SM-like couplings}.$$

- Two realizations:
  - **Decoupling alignment:** $m_H, m_A, m_{H^\pm} \gg v$ automatically drives $\cos(\beta - \alpha) \to 0$.
  - **Alignment without decoupling:** achieved by relations between quartic couplings (e.g. specific relations among λ_i), allowing non-SM Higgs bosons to be **light** and still satisfy Higgs precision data.

Motivation: Vector-Like Quarks (VLQs)

- **Vector-like quarks** are hypothetical colored fermions whose left- and right-handed components transform identically under $SU(2)_L$:
$$Q_L \sim Q_R \sim (3,\, R_{SU(2)},\, Y).$$
- Their **Dirac mass term** is gauge invariant:
$$\mathcal{L} \supset -M\,\bar{Q}Q,$$
- VLQs naturally appear in many well-motivated BSM frameworks:
  - ★ Composite Higgs models (partial compositeness),
  - ★ extra-dimensional models,
  - ★ E_6 GUTs,
  - ★ extended Higgs sectors such as the 2HDM,
- Through mixing with SM quarks, VLQs modify:
  - ★ Higgs couplings (affecting hgg, $h\gamma\gamma$),
  - ★ charged-current interactions (Wtb, WTb),
  - ★ neutral currents (Ztt, Zbb),
  - ★ Yukawa structures in extended Higgs models.
- **Decay modes** depend on the representation:
$$T \to tH,\; tZ,\; bW, \qquad B \to bH,\; bZ,\; tW.$$
- **Production at hadron colliders:**
  - ★ Pair production: dominated by QCD, **model independent**.
  - ★ Single production: controlled by electroweak mixing and Yukawa structure.

VLQ Representations under $SU(2)_L$

- Vector-like quarks can appear in **three possible** $SU(2)_L$ representations:

$$R_{SU(2)} = \mathbf{1},\ \mathbf{2},\ \mathbf{3}.$$

  Each choice dictates the electric charges and possible mixings with SM quarks.

- The complete set of anomaly-free VLQ multiplets is:

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Electric Charges Q
T	3	1	$2/3$	$2/3$
B	3	1	$-1/3$	$-1/3$
TB	3	2	$1/6$	$(2/3,\ -1/3)$
XT	3	2	$7/6$	$(5/3,\ 2/3)$
BY	3	2	$-5/6$	$(-1/3,\ -4/3)$
TBY	3	3	$-1/3$	$(2/3,\ -1/3,\ -4/3)$
XTB	3	3	$2/3$	$(5/3,\ 2/3,\ -1/3)$

- Key phenomenological features:
  - Singlets mix only with one SM quark (e.g. T-t or B-b mixing).
  - Doublets allow mixing patterns controlled by multiple Yukawa parameters.
  - Triplets give more constrained mixing structures and richer couplings.

- In extended Higgs sectors (2HDM, composite Higgs), VLQs couple to all physical scalars $h,\ H,\ A,\ H^{\pm}$, generating novel decay channels and distinctive collider signatures.

Vector-Like Quark Yukawa Structure and Mixing

- In the **Higgs basis**, only one doublet acquires a vev:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix},$$

  where H_2 contains all non-SM Higgses.

- The general VLQ Yukawa Lagrangian for an up-type VLQ T is:

$$\mathcal{L}_Y \supset -y^u_{33}\bar{Q}^0_L\tilde{H}_1\, t^0_R - y^u_{34}\bar{Q}^0_L\tilde{H}_1\, T^0_R - y^u_{43}\bar{T}^0_L\tilde{H}_1\, t^0_R - M^0\bar{T}^0_L T^0_R + \text{h.c.}$$

- After EWSB, the mass Lagrangian takes the form:

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{t}^0_L & \bar{T}^0_L \end{pmatrix} \begin{pmatrix} y^u_{33}\frac{v}{\sqrt{2}} & y^u_{34}\frac{v}{\sqrt{2}} \\ y^u_{43}\frac{v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} t^0_R \\ T^0_R \end{pmatrix} + \text{h.c.}$$

  A 2×2 non-hermitian matrix requiring **bi-unitary** diagonalization.

- The weak→mass basis transformation reads:

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^u_{L,R} & -\sin\theta^u_{L,R}\, e^{i\phi_u} \\ \sin\theta^u_{L,R}\, e^{-i\phi_u} & \cos\theta^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}.$$

- The physical masses satisfy:

$$U^u_L\,\mathcal{M}^u (U^u_R)^\dagger = \text{diag}(m_t,\ m_T).$$

- **Representation-dependent mixing:**

$$\tan\theta^q_R = \frac{m_q}{m_Q}\,\tan\theta^q_L \ \ \text{(VLQ singlet)},$$

$$\tan\theta^q_L = \frac{m_q}{m_Q}\,\tan\theta^q_R \ \ \text{(VLQ doublet)}.$$

  This reduces many parameters to one mixing angle per sector.

☆ **Minimal parametrization:** All VLQ representations can be described by only two free parameters: the heavy mass m_Q and a single mixing angle. The only exception is the TB **doublet**, which requires two mixings (s^u_R, s^d_R).

Representation	T	B	TB	XT	BY	TBY	XTB
Free parameters	$m_T,\, s^u_L$	$m_B,\, s^d_L$	$m_T,\, s^u_R,\, s^d_R$	$m_T,\, s^u_R$	$m_B,\, s^d_R$	$m_T,\, s^u_L$	$m_T,\, s^u_L$

☆ **Charged Higgs interactions** $(H^+tb,\ H^+Tb)$:

$$\mathcal{L}_{H^+} = -\frac{g m_T}{\sqrt{2} M_W}\bar{T}\left(\cot\beta\, Z^L_{Tb} P_L + \tan\beta\, Z^R_{Tb} P_R\right) b\, H^+ - \frac{g m_t}{\sqrt{2} M_W}\bar{t}\left(\cot\beta\, Z^L_{tb} P_L + \tan\beta\, Z^R_{tb} P_R\right) b\, H^+ + \text{h.c.}$$

2HDM-II + TB Doublet

$$Z^L_{tb} = c^d_L c^u_L + \frac{s^d_L}{s^u_L}\left({s^u_L}^2 - {s^u_R}^2\right) e^{i(\phi_u - \phi_d)},$$

$$Z^R_{tb} = \frac{m_b}{m_t}\left[c^u_L c^d_L + \frac{s^u_L}{s^d_L}\left({s^d_L}^2 - {s^d_R}^2\right) e^{i(\phi_u - \phi_d)}\right],$$

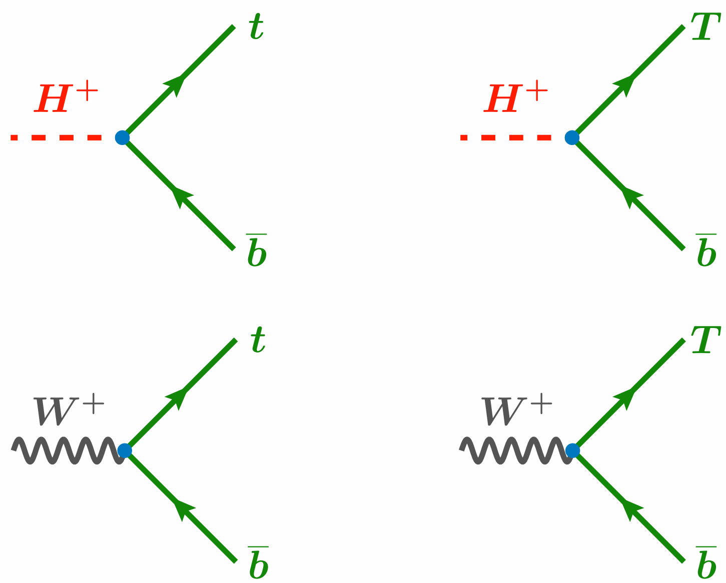
$$Z^L_{Tb} = c^d_L s^u_L\, e^{-i\phi_u} + \left({s^u_L}^2 - {s^u_R}^2\right)\frac{s^d_L}{c^u_L}\, e^{-i\phi_d},$$

$$Z^R_{Tb} = \frac{m_b}{m_T}\left[c^d_L s^u_L\, e^{-i\phi_u} + \left({s^d_R}^2 - {s^d_L}^2\right)\frac{c^u_L}{s^d_L}\, e^{-i\phi_d}\right].$$

☆ W^+ **boson interaction** (W^+Tb):

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\bar{T}\gamma^\mu\left(V^L_{Tb} P_L + V^R_{Tb} P_R\right) b\, W^+_\mu + \text{h.c.}$$

$$V^L_{Tb} = s^u_L c^d_L\, e^{-i\phi_u} - c^u_L s^d_L\, e^{-i\phi_d},$$
$$V^R_{Tb} = -c^u_R s^d_R\, e^{-i\phi_d}.$$



Global Constraints on the 2HDM+VLQ Framework

Theoretical Constraints

- **Unitarity** The full scalar-scalar scattering matrix (including VLQ-induced corrections to quartics) must satisfy:

$$|a_0| < \tfrac{1}{2}.$$

- **Perturbativity** All scalar and Yukawa couplings satisfy:

$$|\lambda_i| < 8\pi, \qquad |y_{ij}^{u,d}| < \sqrt{4\pi}.$$

- **Vacuum stability** The scalar potential must remain bounded from below:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

`2HDMC-1.8.0`

D. Eriksson, J. Rathsman, O. Stål (0902.0851)

Experimental Constraints

- **Electroweak Precision Observables (EWPO)** The combined (2HDM + VLQ) contributions to the oblique parameters must satisfy:

$$\Delta\chi^2\left(S^{2HDM} + S^{VLQ},\ T^{2HDM} + T^{VLQ}\right) \leq 6.18,$$

corresponding to a 95% CL ellipse.

- **SM-like Higgs measurements** Compatibility with LHC Run 2 and Run 3 signal-strength data is enforced via:

`HiggsSignals-3` (through `HiggsTools`).

- **BSM Higgs searches** Exclusion limits from LEP, Tevatron and LHC for H, A and $H^\pm$ are applied using:

`HiggsBounds-6` (via `HiggsTools`).

- **Flavour Observables** Including $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$, $B \to \tau\nu$, ΔM_{B_s}, etc., evaluated using:

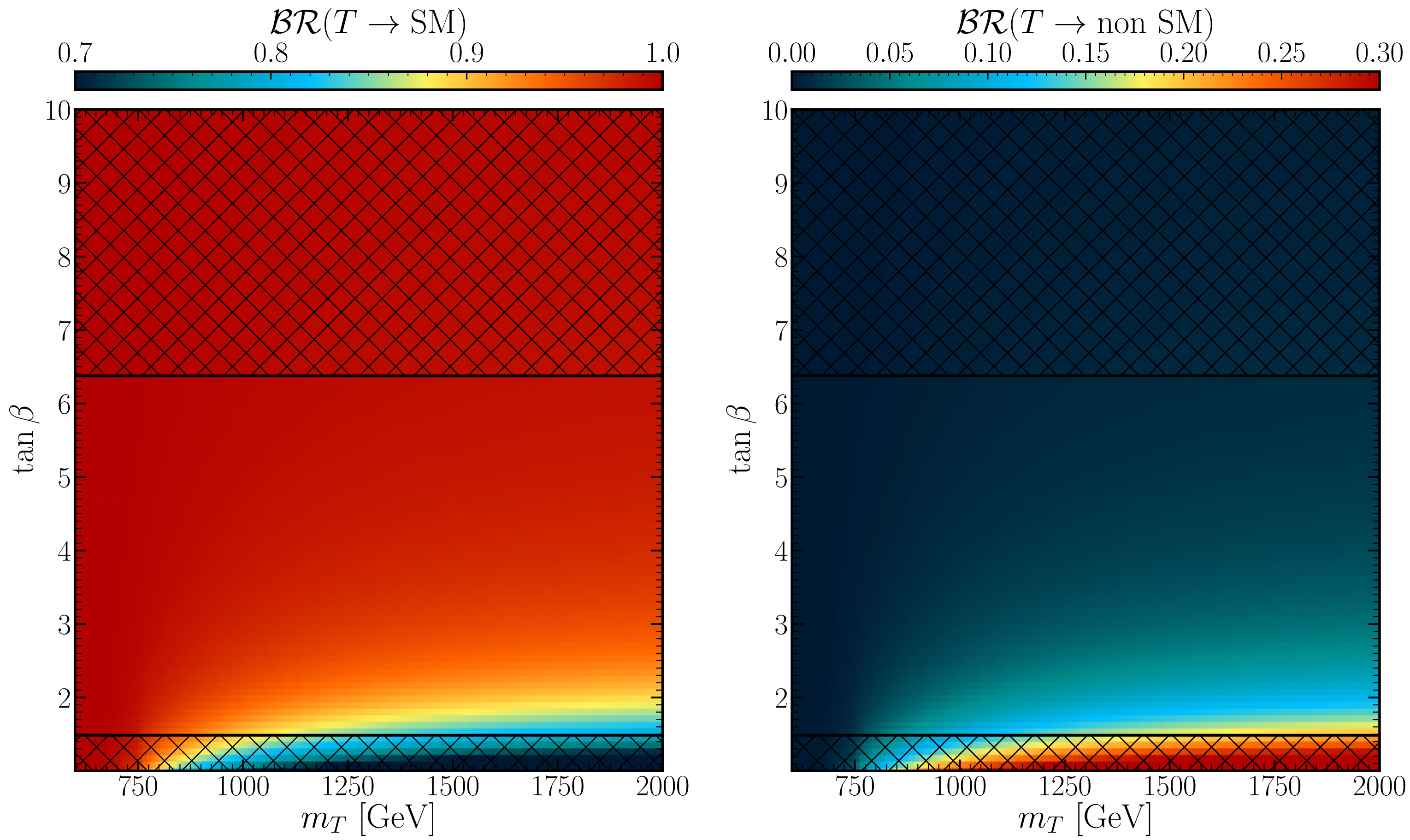
`SuperIso-v4.1`.

- **Direct VLQ searches (LHC)** Current ATLAS/CMS limits primarily target SM-like decay channels:

$$T \to bW,\ tZ,\ tH, \qquad B \to tW,\ bZ,\ bH.$$

Benbrik, Boukidi, Ech-chaouy, Moretti, Salime, JHEP 03 (2025)

2HDM-II + T Singlet Scenario



- For an $SU(2)_L$ **singlet** T, mixing with the SM top proceeds only via s_L^u, yielding suppressed scalar couplings.
- Approximate Goldstone-controlled pattern:

$$\Gamma(T \to bW) : \Gamma(T \to tZ) : \Gamma(T \to th) \approx 2 : 1 : 1.$$

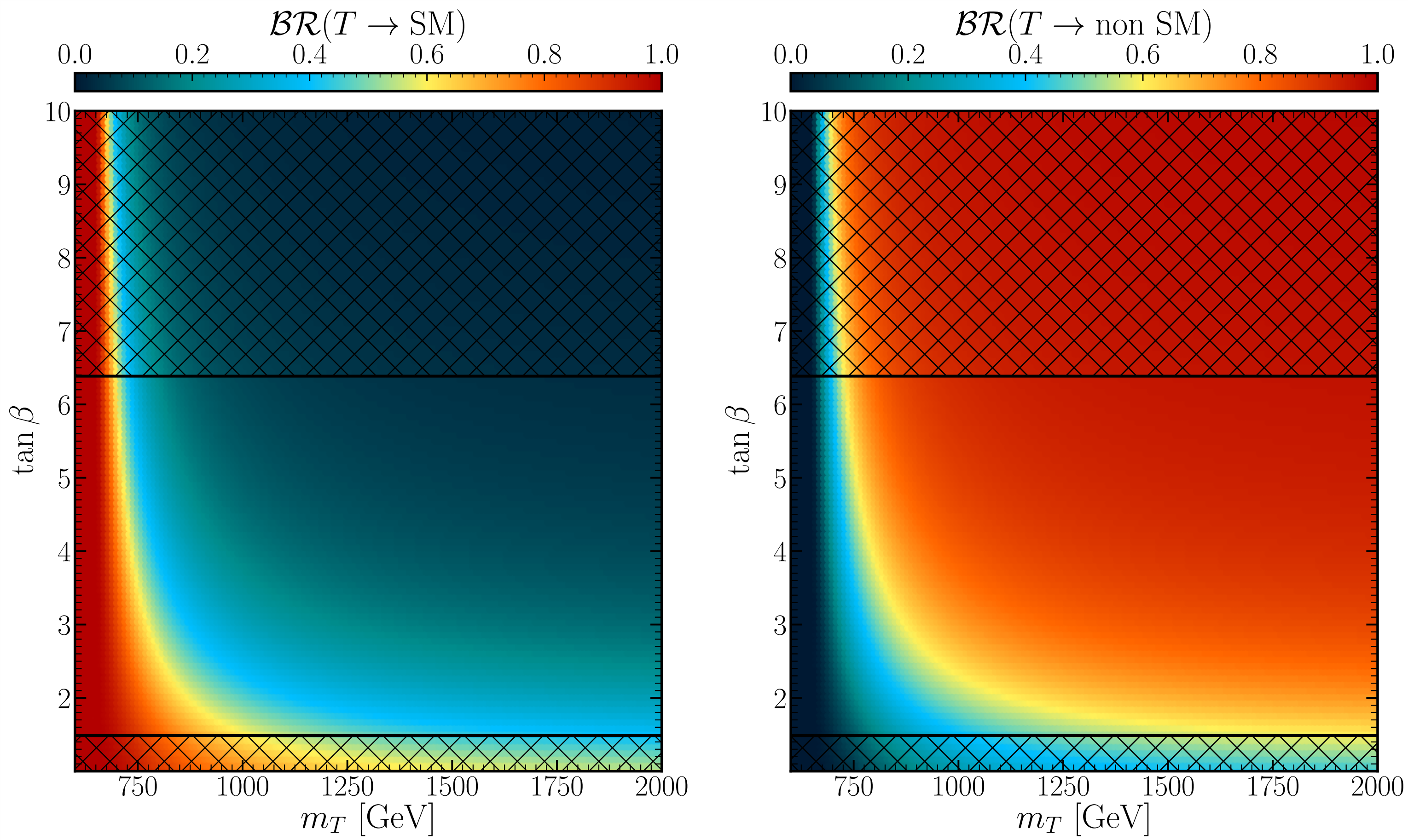
- SM decay channels dominate across the $(m_T, \tan\beta)$ plane:

$$T \to bW, \quad tZ, \quad th.$$

- Exotic channels $T \to tH,\ tA,\ H^+b$ are highly suppressed.

Arhrib, Benbrik, Boukidi, Manaut, Moretti Eur.Phys.J.C 85 (2025) 1, 2

2HDM-II + TB Doublet Scenario



- In the (T, B) **doublet**, scalar interactions are unsuppressed due to left-handed doublet quantum numbers.
- Yukawa couplings to H, A, $H^{\pm}$ scale as $\mathcal{O}(1)$, not mixing-suppressed.
- Dominant decay modes:

$$T \to Ht, \qquad T \to At, \qquad T \to H^{+}b.$$

- The doublet Yukawa structure reorders the spectrum of partial widths, enhancing exotic channels.
- Standard ATLAS/CMS searches assuming only SM decays can miss this region: a potential **LHC blind spot**.

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MC Simulation Framework

- **Collider analyses performed in this work:**
  - ★ **Fully hadronic analysis** (multi-b):

$$pp \to T\bar{T} \;\to\; (H^+b)(H^-\bar{b}) \;\Rightarrow\; 2t4b \quad (4b,\; 5b\,\text{final states}).$$

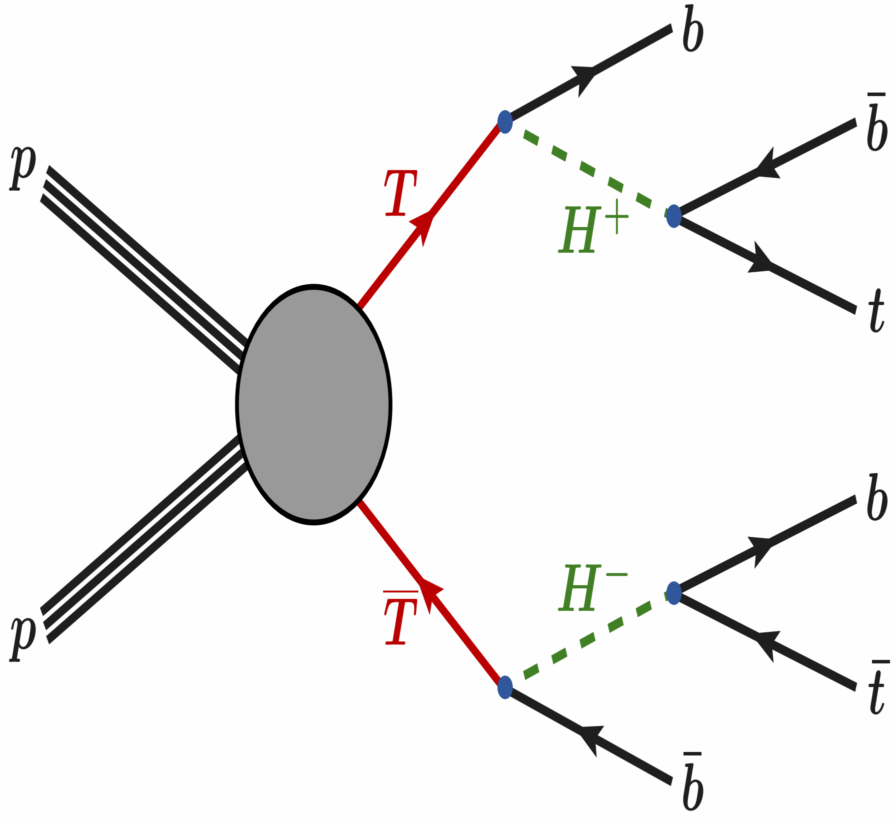
  - ★ **Semi-leptonic analysis**:

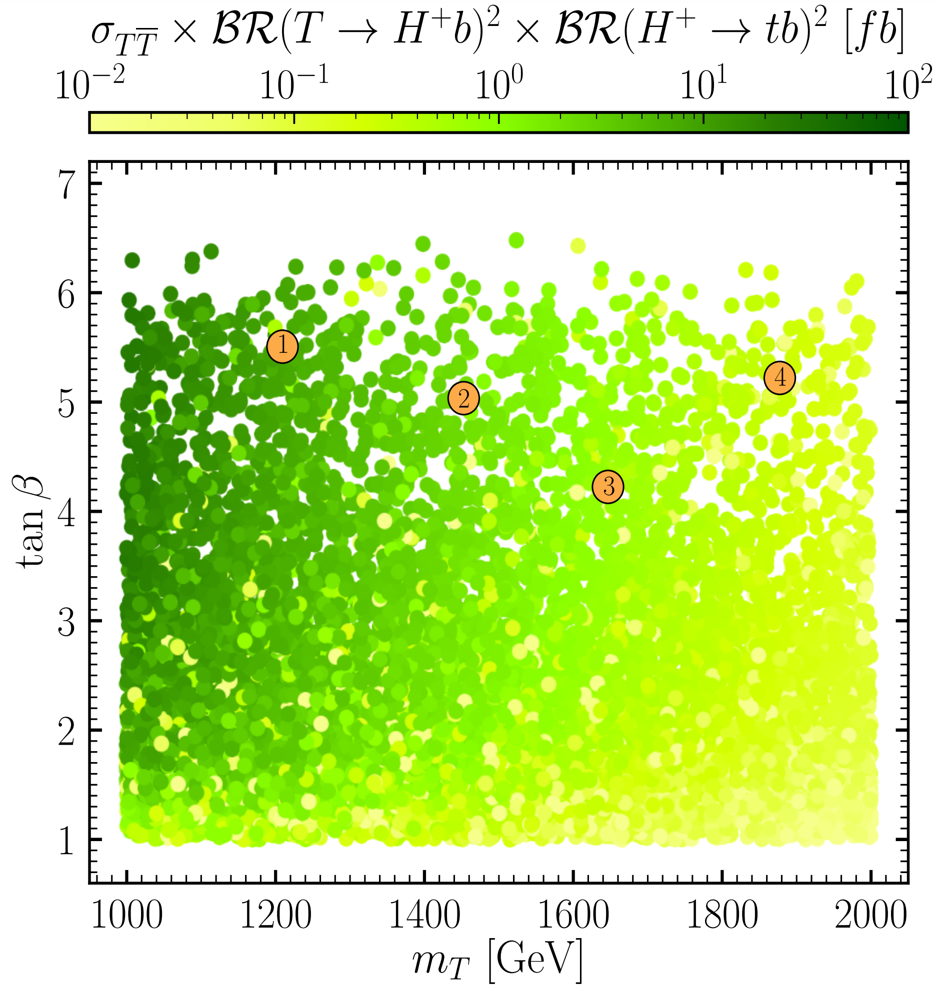
$$pp \to T\bar{T} \;\to\; (H^+b)(H^-\bar{b}) \;\Rightarrow\; \ell^+\ell^- + 6b + \not{E}_T.$$

- **Simulation pipeline:**
  - ★ `MadGraph5_aMC@NLO` hard-scattering event generation.
  - ★ `Pythia8` parton showering and hadronisation.
  - ★ `Delphes` detector response.
  - ★ `FastJet` anti-k_T jet clustering.
  - ★ `MadAnalysis5` cutflow and event selection.

- **Discovery significance including systematics (δ):**

$$\boxed{\mathcal{Z}_{disc} = \sqrt{2\left[(s+b)\ln\left(\frac{(s+b)(1+\delta^2 b)}{b+\delta^2 b(s+b)}\right) - \frac{1}{\delta^2}\ln\left(1+\frac{\delta^2 s}{1+\delta^2 b}\right)\right]}}$$



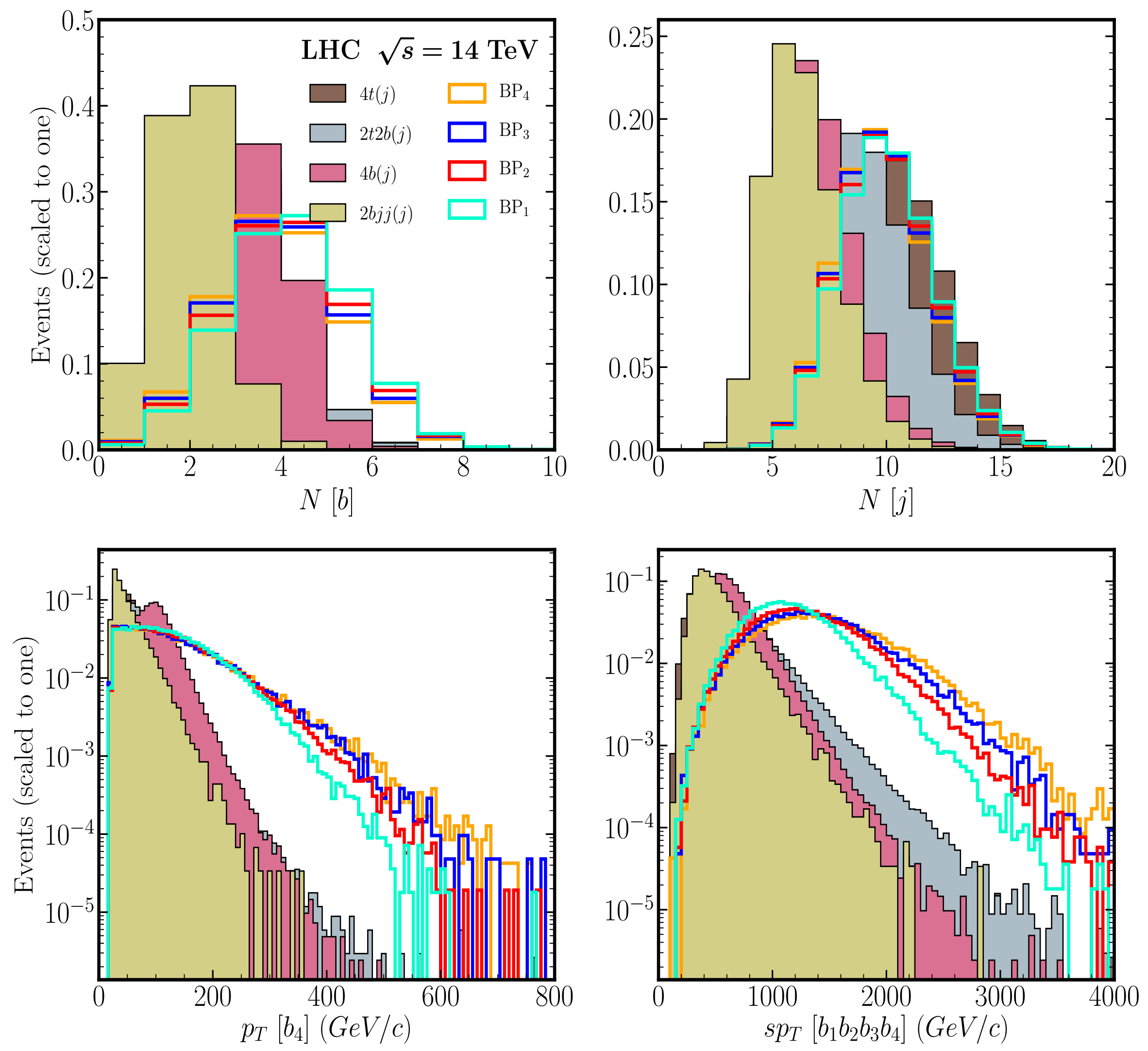


- Feynman diagrams for $pp \to T\bar{T}$ and decays leading to $4b + 2t$.
- Signal: $pp \to T\bar{T} \to (bH^+)(\bar{b}H^-) \to (b(tb))(\bar{b}(\bar{t}b))$.
- Signal regions: $N(b) \geq 4$ and $N(j) \geq 8$, $N(b) \geq 5$ and $N(j) \geq 8$.
- Main backgrounds: $t\bar{t}t\bar{t}(j)$, $t\bar{t}b\bar{b}j$, $4b\,j$, and $2b$ jets.

- $\sigma_{TT} \times \mathcal{BR}(T \to H^+ b)^2 \times \mathcal{BR}(H^+ \to t\bar{b})^2$ vs. m_T and $\tan\beta$ in 2HDM-II+TB. Orange circles mark the selected BPs.

Arhrib, Benbrik, Berrouj, Boukidi, Manaut Phys.Rev.D 111 (2025) 9, 095026

$4b$ ANALYSIS



☆ Distributions of $N(b)$, $N(j)$, $p_T(b_4)$, and $sp_T(b_1b_2b_3b_4)$ for BPs (BP$_1$-BP$_4$) and backgrounds at $\sqrt{s} = 14$ TeV.

Cuts	Definition
Cut 1	$N(b) \geq 4$, $N(j) \geq 8$
Cut 2	$sp_T > 1400$ GeV
Cut 3	$p_T^{b_4} > 140$ GeV

☆ Cut set for signal/background at $\sqrt{s} = 14$ TeV.

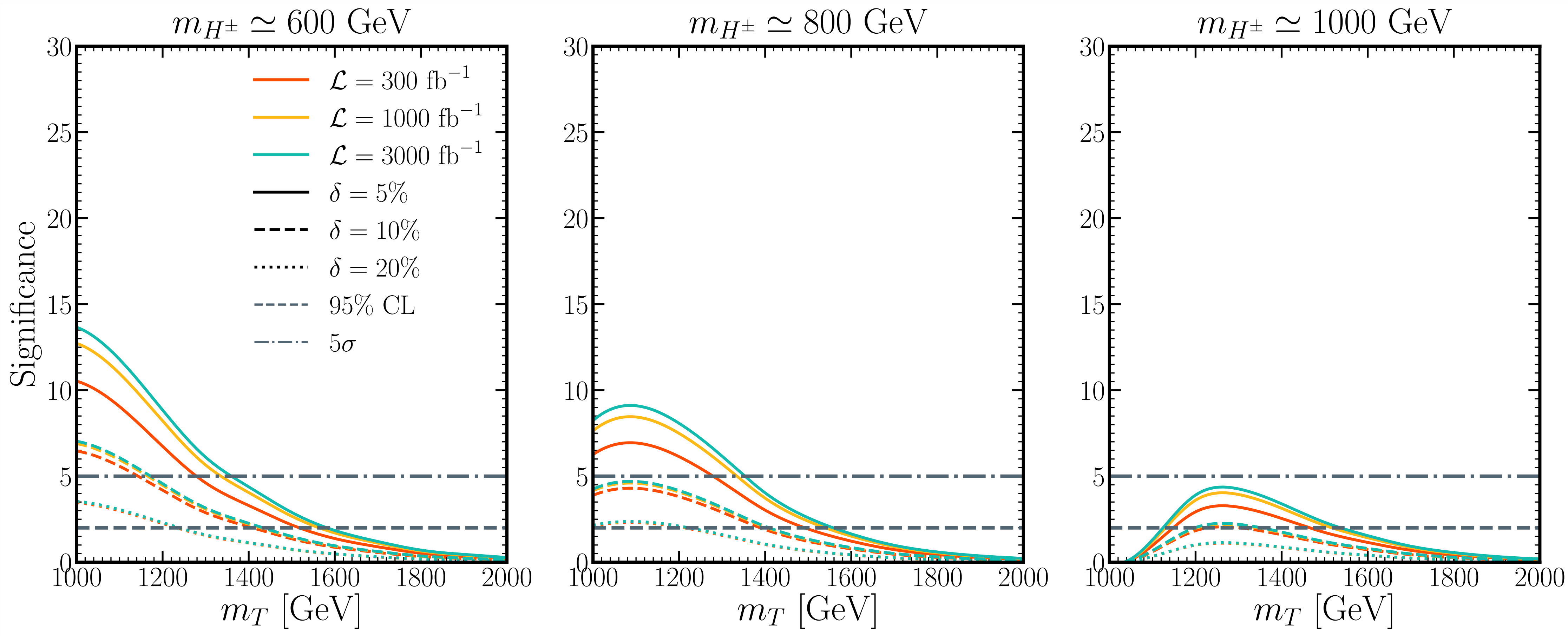
Cuts	**Signals**				**Backgrounds**			
	BP1	BP2	BP3	BP4	2bjets	$4bj$	$2t2bj$	$4tj$
Basic	10.36	1.95	0.819	0.283	240725	757.74	202.56	16.60
Cut 1	4.41	0.760	0.31	0.093	1005.20	32.9	29.60	3.07
Cut 2	1.00	0.272	0.13	0.045	5.60	0.33	0.543	0.033
Cut 3	0.67	0.168	0.08	0.026	0.96	0.179	0.18	0.008
Efficiency	6.48%	8.83%	9.70%	9.74%	2.93×10^{-6}	2.45×10^{-4}	9.39×10^{-4}	4.94×10^{-4}

☆ Cutflow of cross sections (fb) for signal and SM backgrounds at $\sqrt{s} = 14$ TeV.

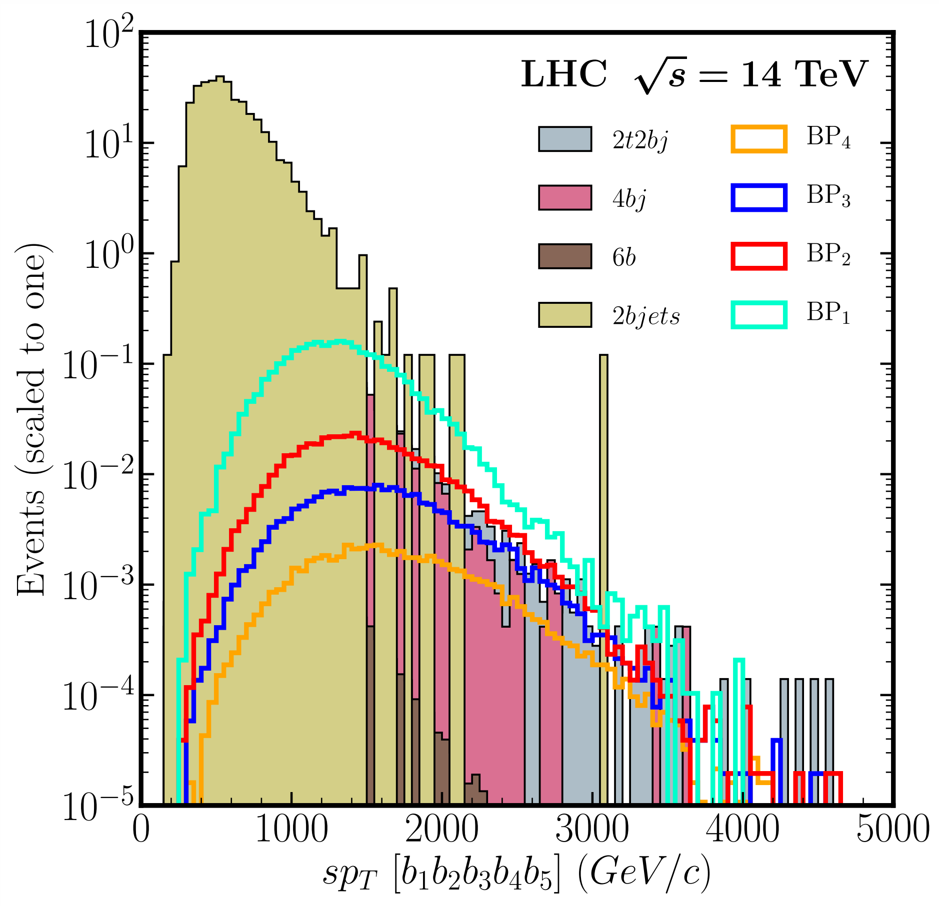
$4b$ Analysis

m_T [GeV]	$\mathcal{L} = 300$ fb^{-1}			$\mathcal{L} = 1000$ fb^{-1}			$\mathcal{L} = 3000$ fb^{-1}		
	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$
1000.0	10.53	6.47	3.47	12.73	6.90	3.53	13.66	7.04	3.55
1100.0	9.05	5.58	2.99	10.97	5.96	3.05	11.79	6.08	3.06
1200.0	6.74	4.18	2.25	8.21	4.47	2.29	8.85	4.56	2.30
1300.0	4.61	2.88	1.55	5.65	3.08	1.58	6.10	3.15	1.59
1400.0	3.30	2.06	1.11	4.05	2.22	1.14	4.38	2.27	1.14
1500.0	2.17	1.36	0.74	2.67	1.46	0.75	2.90	1.50	0.76
1600.0	1.38	0.87	0.47	1.70	0.93	0.48	1.85	0.95	0.48
1700.0	0.90	0.56	0.31	1.11	0.61	0.31	1.20	0.62	0.31
1800.0	0.52	0.33	0.18	0.65	0.36	0.18	0.70	0.36	0.18
1900.0	0.34	0.21	0.12	0.42	0.23	0.12	0.46	0.24	0.12
2000.0	0.20	0.12	0.07	0.24	0.13	0.07	0.26	0.14	0.07

- Discovery significance $\mathcal{Z}_{disc}$ for the $4b$ analysis shown for different systematics (δ) and integrated luminosities $\mathcal{L} = 300,\ 1000,\ 3000$ fb^{-1}.
- Fixed parameters: $m_H = 600.26$ GeV, $m_A = 595.24$ GeV, $m_{H^\pm} = 658.07$ GeV, $\tan\beta = 6$, $s_R^u = 0.05$, $s_R^d = 0.11$.
- Significance vs. m_T for $m_{H^\pm} = 600$ GeV (left), 800 GeV (center), and 1000 GeV (right).



$5b$ Analysis



☆ sp_T distribution for BPs and backgrounds in the $5b$ analysis.

☆ Cut set for signal/background at $\sqrt{s} = 14$ TeV.

Cuts	Definition
Cut 1	$N(b) \geq 5$, $N(j) \geq 8$
Cut 2	$sp_T > 1500$ GeV
Cut 3	$p_T^{b_4} > 120$ GeV

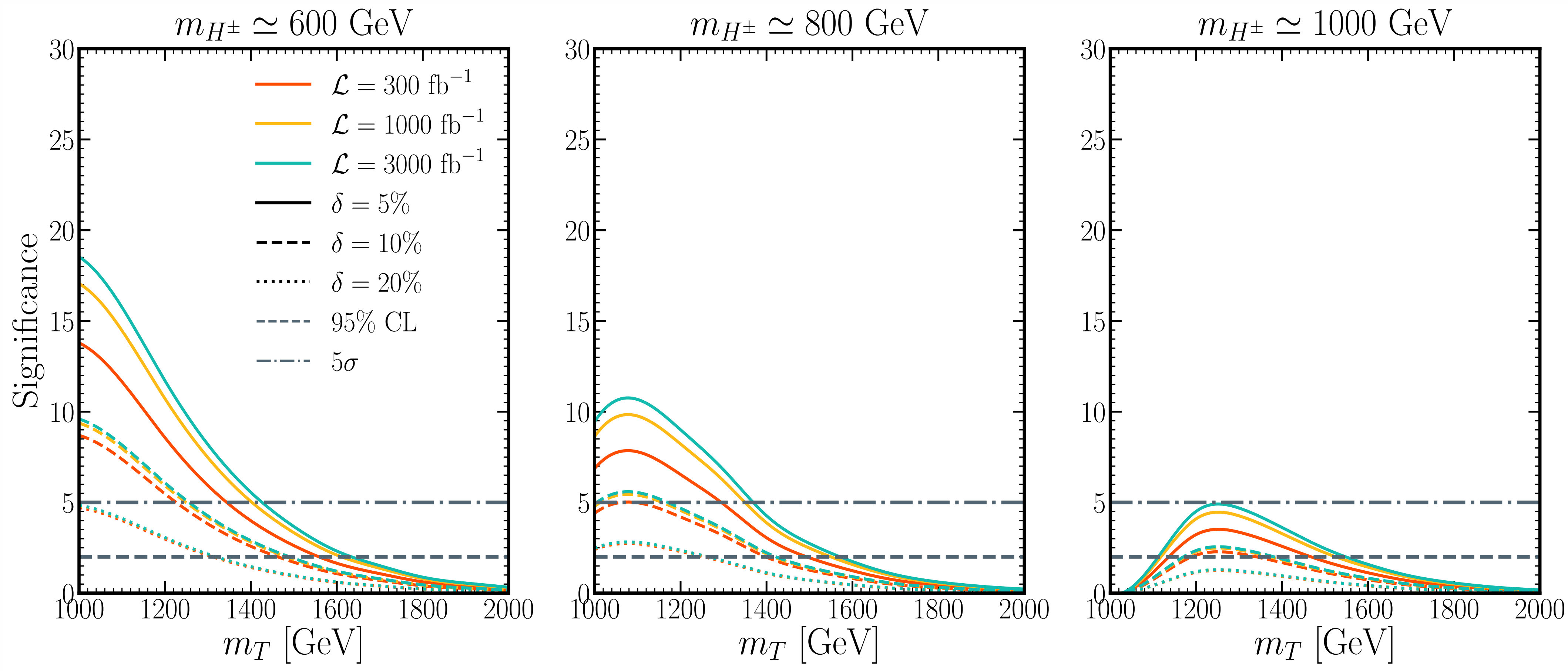
☆ Cutflow of cross sections (fb) for signals and SM backgrounds at $\sqrt{s} = 14$ TeV for the three typical BPs.

Cuts	Signals				Backgrounds			
	BP1	BP2	BP3	BP4	$2b$jets	$4bj$	$2t2bj$	$6b$
Basic	10.36	1.95	0.82	0.28	3240775	727.74	202.56	0.14
Cut 1	2.76	0.47	0.18	0.054	241.7	16.4	10.21	0.040
Cut 2	0.84	0.21	0.096	0.032	0.84	0.18	0.28	0.0015
Cut 3	0.73	0.18	0.08	0.026	0.722	0.145	0.18	0.0013
Efficiency	7.09%	9.17%	9.75%	9.73%	2.23×10^{-6}	1.99×10^{-4}	8.81×10^{-4}	9.40×10^{-3}

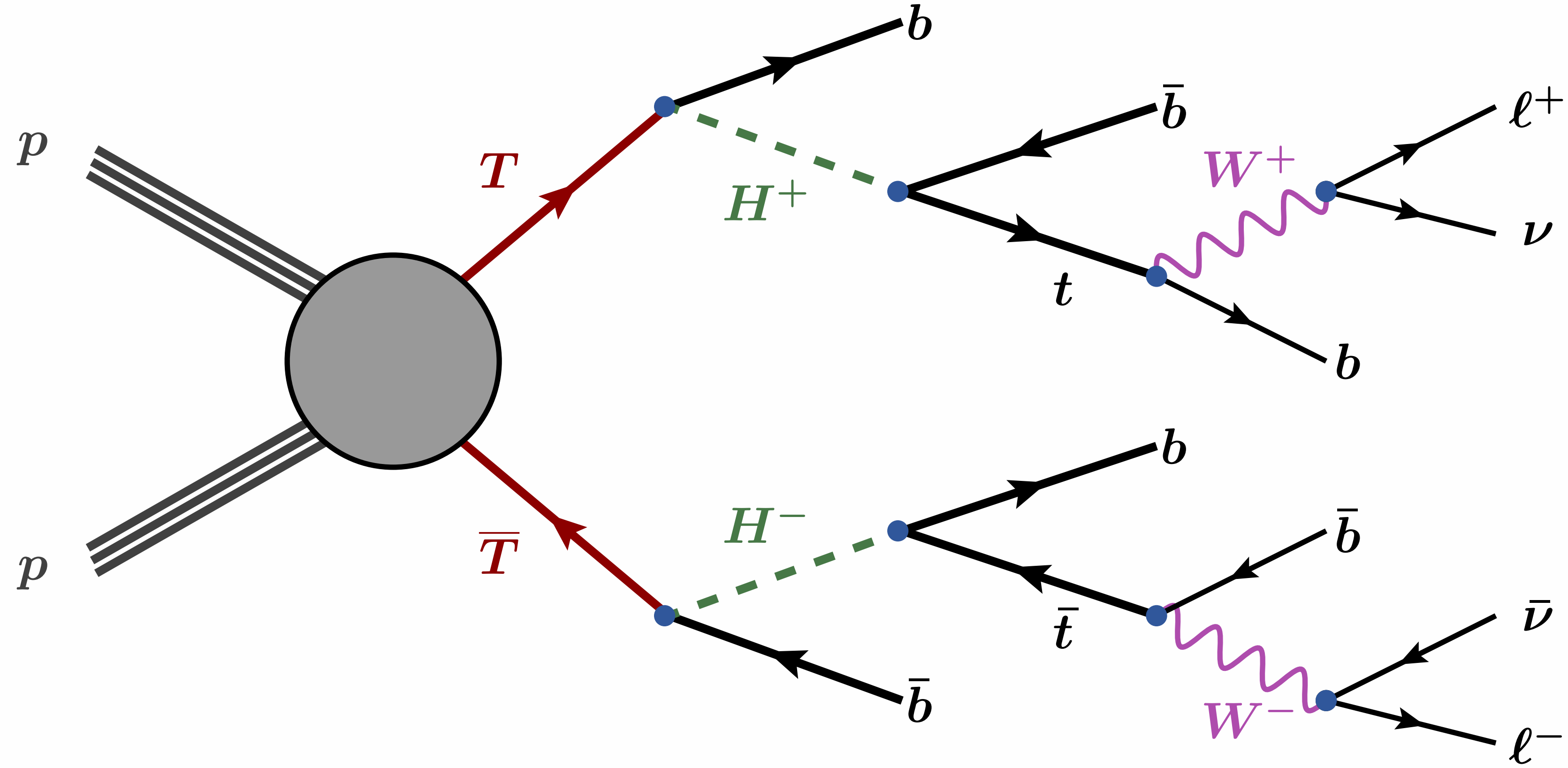
$5b$ Analysis

m_T [GeV]	$\mathcal{L} = 300$ fb^{-1}			$\mathcal{L} = 1000$ fb^{-1}			$\mathcal{L} = 3000$ fb^{-1}		
	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$
1000.0	13.79	8.69	4.71	17.06	9.37	4.81	18.53	9.60	4.84
1100.0	11.65	7.38	4.01	14.47	7.97	4.10	15.75	8.17	4.12
1200.0	8.57	5.47	2.98	10.72	5.93	3.05	11.71	6.08	3.07
1300.0	5.93	3.81	2.09	7.47	4.15	2.14	8.19	4.26	2.15
1400.0	3.99	2.58	1.42	5.05	2.81	1.45	5.55	2.89	1.46
1500.0	2.62	1.70	0.94	3.33	1.86	0.96	3.67	1.91	0.97
1600.0	1.65	1.07	0.59	2.10	1.17	0.61	2.32	1.21	0.61
1700.0	1.07	0.70	0.39	1.37	0.77	0.40	1.51	0.79	0.40
1800.0	0.62	0.41	0.22	0.80	0.45	0.23	0.88	0.46	0.23
1900.0	0.39	0.26	0.14	0.50	0.28	0.15	0.55	0.29	0.15
2000.0	0.22	0.15	0.08	0.29	0.16	0.08	0.32	0.17	0.08

- Discovery significance $\mathcal{Z}_{disc}$ for the $5b$ analysis shown for different systematics (δ) and luminosities ($\mathcal{L} = 300, 1000, 3000$ fb^{-1}).
- Fixed parameters: $m_H = 600.26$ GeV, $m_A = 595.24$ GeV, $m_{H^\pm} = 658.07$ GeV, $\tan\beta = 6$, $s_R^u = 0.05$, $s_R^d = 0.11$.
- Significance vs. m_T for $m_{H^\pm} = 600$ GeV (left), 800 GeV (center), and 1000 GeV (right).



Final state with multiple b-jets and opposite-sign dilepton



- Feynman diagrams for $T\bar{T}$ pair production with subsequent decays into opposite-sign dileptons, multiple b-jets, and missing transverse energy from neutrinos.
- Signal: $l^+ + l^- + 6b + \not{E}_T$
- Backgrounds: $t\bar{t}b\bar{b}(j)$, $t\bar{t}$+jets, $t\bar{t}W(j)$, $t\bar{t}Z(j)$, $t\bar{t}h(j)$, $t\bar{t}t\bar{t}$

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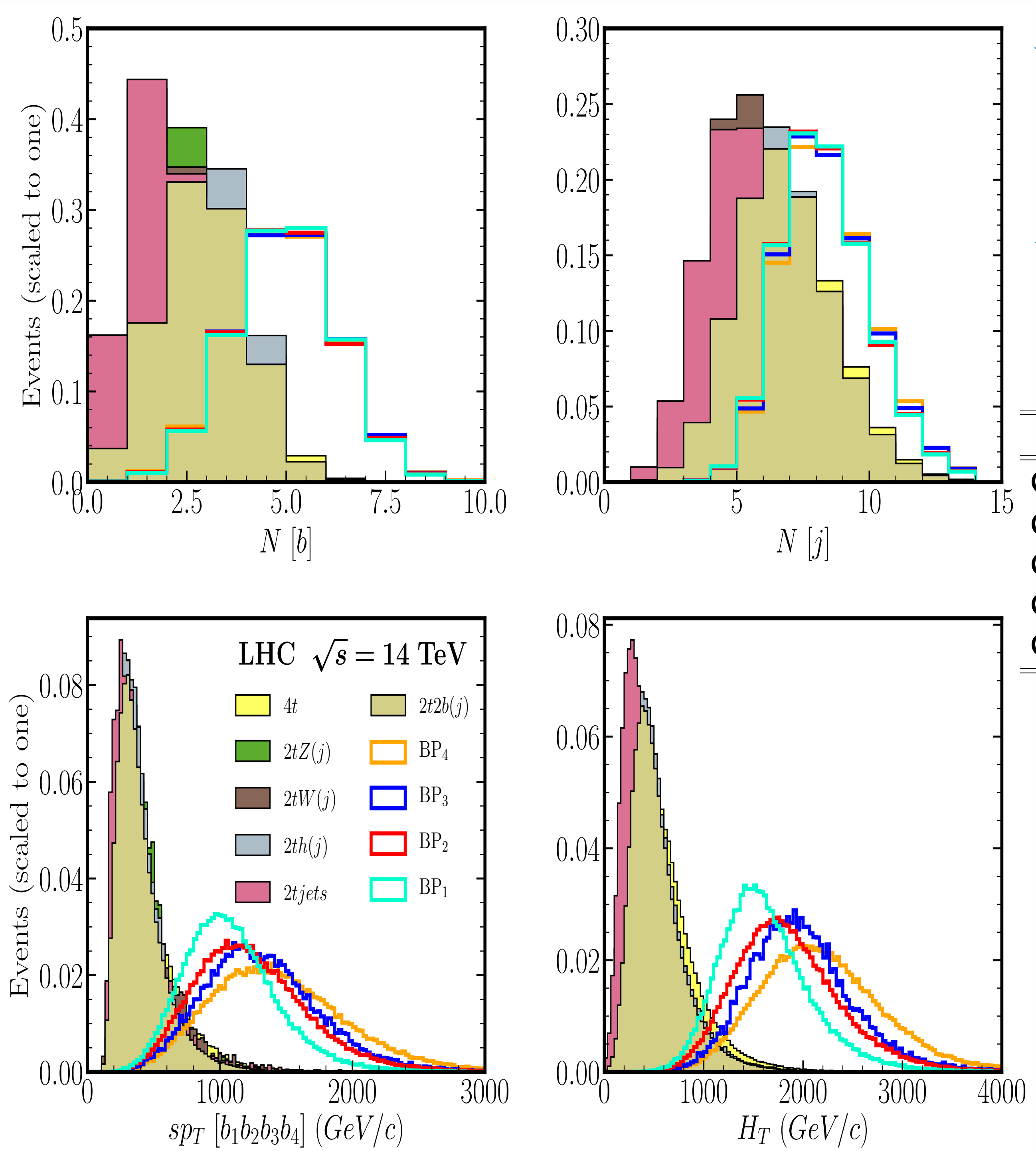
Results



- Distributions of $N(b)$, $N(j)$, $sp_T(b_1b_2b_3b_4)$, and H_T for signal benchmarks (BP$_1$-BP$_4$) and backgrounds at $\sqrt{s} = 14$ TeV.
- Event selection cuts applied at $\sqrt{s} = 14$ TeV:

Cuts	Definition
Cut 1	$N(b) \geq 4$, $N(j) \geq 5$, $N(l^-) = 1$, $N(l^+) = 1$
Cut 2	$p_T(l^\pm) > 20$ GeV
Cut 3	$p_T(b_1) > 300$ GeV, $p_T(b_4) > 40$ GeV
Cut 4	$sp_T > 900$ GeV
Cut 5	$H_T > 1500$ GeV

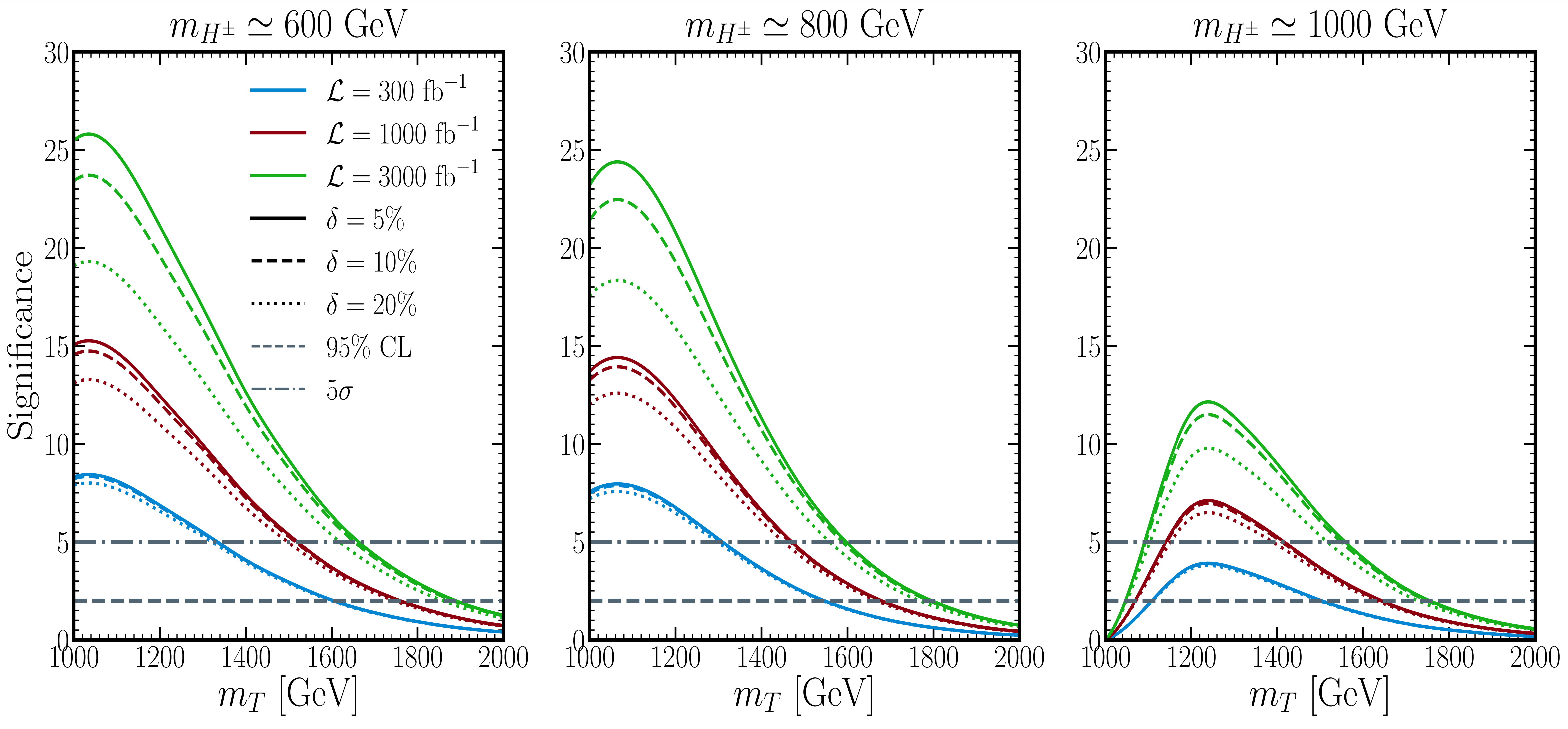
Results

Cuts	Signals				Backgrounds					
	$BP1$	$BP2$	$BP3$	$BP4$	$2t2b(j)$	$2t$+jets	$2tW(j)$	$2tZ(j)$	$2th(j)$	$4t$
Basic	33.8	7.3	6.0	0.84	5828	467702	43621	3463	2419	305
Cut1	7.34	1.59	1.26	0.18	31.3	105.6	0.10	3.13	11.1	3.16
Cut2	6.29	1.36	1.11	0.16	26.5	81.9	0.08	2.48	9.90	2.53
Cut3	5.34	1.25	1.02	0.15	2.37	5.45	0.01	0.21	0.65	0.42
Cut4	4.57	1.12	0.96	0.14	0.53	1.81	0.002	0.09	0.14	0.15
Cut5	3.24	0.95	0.88	0.13	0.14	0	0.002	0	0	0.07
Eff.	9.6%	13.0%	14.7%	15.5%	2.4×10^{-5}	0	4.1×10^{-8}	0	0	1.7×10^{-4}

- ✯ Cutflow for signals and backgrounds at $\sqrt{s} = 14$ TeV; cross sections in 10^{-2} fb.
- ✯ $\mathcal{Z}_{disc}$ shown for several systematics δ and luminosities $300,\ 1000,\ 3000\ fb^{-1}$.
- ✯ $m_H = 600.3$ GeV, $m_A = 595.2$ GeV, $m_{H^\pm} = 658.1$ GeV, $\tan\beta = 6$, $s_R^u = 0.05$, $s_R^d = 0.11$.

m_T [GeV]	$\mathcal{L} = 300$ fb^{-1}			$\mathcal{L} = 1000$ fb^{-1}			$\mathcal{L} = 3000$ fb^{-1}		
	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$
1000.0	8.32	8.22	7.90	15.05	14.54	13.11	25.47	23.41	19.08
1100.0	8.11	8.02	7.71	14.67	14.18	12.80	24.83	22.85	18.65
1200.0	6.87	6.80	6.57	12.44	12.08	10.99	21.12	19.58	16.13
1300.0	5.49	5.45	5.28	9.96	9.71	8.93	16.96	15.86	13.23
1400.0	4.07	4.05	3.95	7.40	7.24	6.74	12.63	11.94	10.13
1500.0	2.95	2.93	2.87	5.36	5.27	4.95	9.18	8.75	7.54
1600.0	2.03	2.02	1.99	3.69	3.64	3.45	6.33	6.08	5.33
1700.0	1.38	1.38	1.36	2.52	2.49	2.38	4.33	4.18	3.72
1800.0	0.93	0.93	0.92	1.69	1.68	1.61	2.91	2.82	2.54
1900.0	0.61	0.61	0.60	1.11	1.10	1.06	1.90	1.85	1.68
2000.0	0.40	0.40	0.40	0.73	0.73	0.70	1.26	1.23	1.12

Results



- Discovery significance $\mathcal{Z}_{disc}$ as a function of m_T for three charged Higgs benchmark masses: $m_{H^\pm} = 600$ GeV (left), 800 GeV (center), 1000 GeV (right).
- Results shown for different systematic uncertainties (δ) and luminosities ($\mathcal{L} = 300, 1000, 3000$ fb^{-1}).
- Parameters fixed to $m_H \simeq m_A \simeq m_{H^\pm}$, $\tan\beta = 5$, $s_R^u = 0.05$, $s_R^d = 0.11$.

Conclusions

- The study addressed the pair production of VLT in the 2HDM-II+TB framework, with particular emphasis on the enhanced decay channel
$$T \to H^+ b.$$
- Two complementary collider analyses were developed within this setup:
  - Fully hadronic final states featuring multi-b jet topologies ($4b$ and $5b$).
  - Semi-leptonic final states with opposite-sign dileptons, multiple b jets, and missing transverse energy.
- The resulting discovery significance $\mathcal{Z}_{disc}$ exhibits excellent sensitivity, with the potential to probe VLT masses well into the multi-TeV regime at the HL-LHC.
- The analysis illustrates that exotic decay channels involving charged Higgs bosons offer competitive and in specific regions of parameter space, superior discovery prospects compared to conventional $T \to Wb$, $T \to Zt$, and $T \to ht$ searches.
- Overall, the 2HDM-II+TB scenario remains a compelling framework in which VLQ searches can be significantly enhanced by exploiting non-standard Higgs-mediated final states.